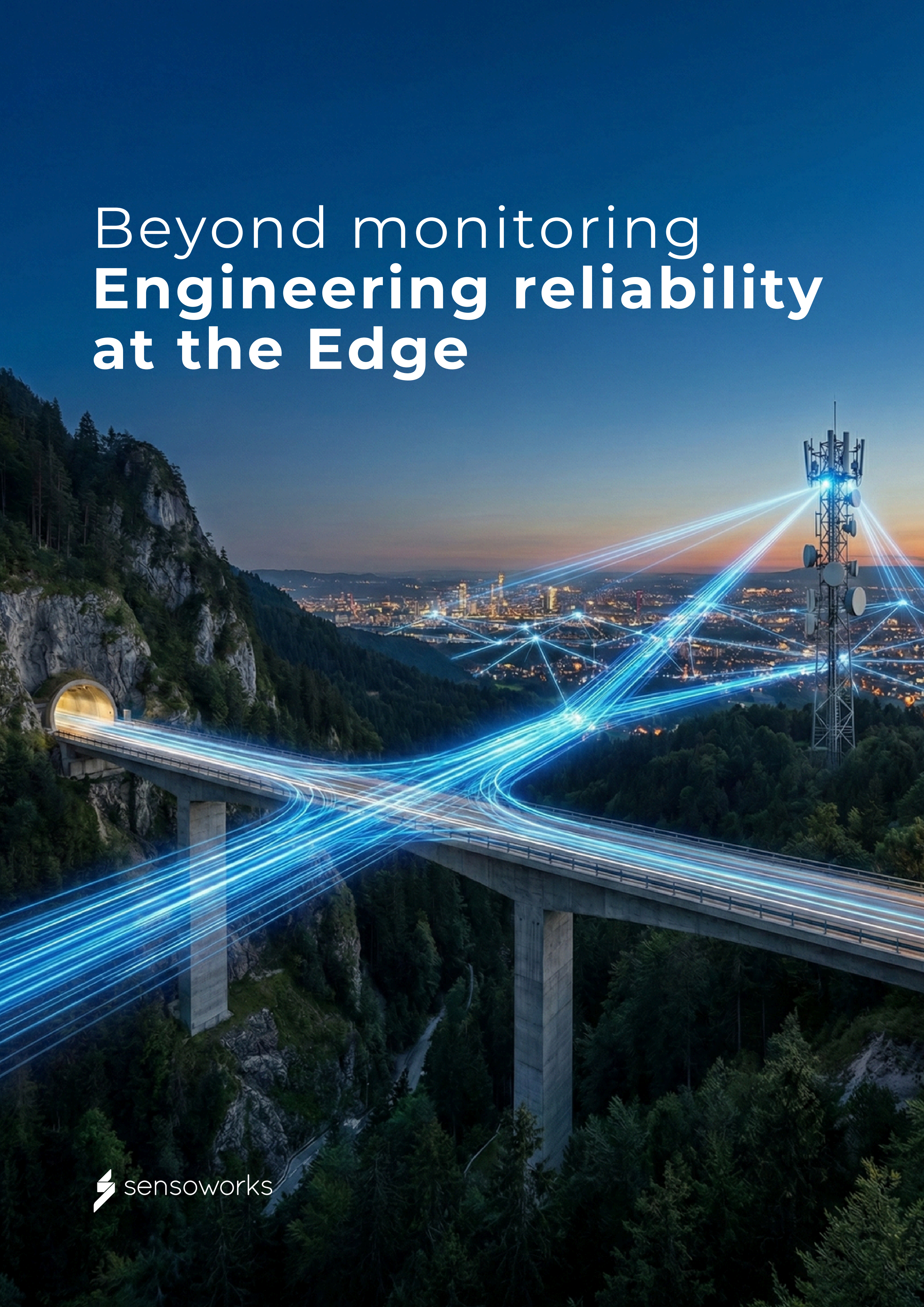
Beyond monitoring **Engineering reliability at the Edge**



sensoworks

Index

Introduction

The growing complexity of modern infrastructure requires a new way of thinking about monitoring and control.
Bridges, tunnels, telecommunications towers, and hydroelectric facilities are dynamic systems exposed to continuous mechanical stress, environmental fluctuations, and operational demands.
Each component interacts with the surrounding environment, producing a constant stream of physical data that can reveal much more than simple status or performance.
However, in many operational contexts, that data remains underused.
Traditional monitoring approaches rely on manual inspections, low-frequency sampling and centralised data processing.
This limits the ability to detect early deterioration or to predict failures before they occur.
The result is a reactive model of maintenance where interventions occur after the problem, not before it.
At Sensoworks, we believe that infrastructures should no longer depend on distance, connectivity or reaction time.
They should think about where they act.
This principle lies at the core of Sensoworks Edge: a distributed computing platform that transforms data into real-time awareness, bringing intelligence directly to the field.
Edge computing enables infrastructures to monitor themselves, learn from their own behaviour and respond autonomously to change.
When data is processed locally, decision-making becomes faster, bandwidth use is reduced, and operational continuity is ensured even in remote or isolated areas.

A new standard of awareness

The goal of Sensoworks Edge is not simply to collect information but to build a living digital ecosystem around the physical asset.
Through a network of sensors, processing units and communication layers, infrastructures become active participants in their own maintenance.
This creates a new operational standard: predictive, resilient, and adaptive.

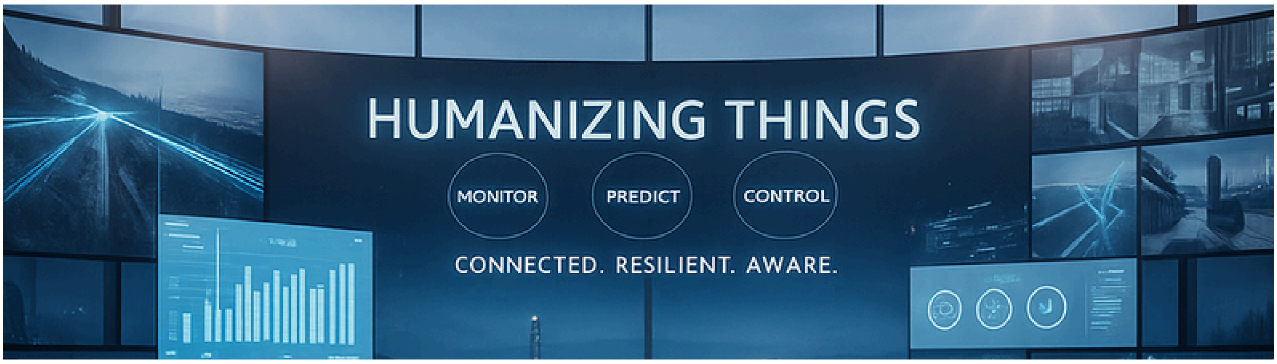
Our mission and vision

Sensoworks empowers operators, engineers, and infrastructure managers to **Monitor, Predict, and Control** critical assets through data that is immediate, contextual, and actionable.
We design software that transforms complex information into clear insights, enabling timely and informed decisions that improve safety, operational continuity, and long-term sustainability.

Our mission is rooted in a simple conviction: technology should support people, simplifying processes and strengthening their ability to manage infrastructures in an increasingly dynamic and demanding world.

Our vision is to create infrastructures that behave like the communities they serve: connected, resilient, and aware.
In this future, infrastructures become intelligent systems capable of understanding their condition, adapting to change, and communicating seamlessly with those who manage them.

This principle is what we call **Humanizing Things,** bringing technology closer to people, making digital intelligence intuitive, accessible, and aligned with real operational needs. Through this approach, Sensoworks aims to redefine the relationship between communities and the built environment, enabling more resilient, efficient, and sustainable cities.



Edge Computing and distributed intelligence

Definition and concept

Edge computing refers to a distributed processing paradigm where computational resources are positioned close to the data source.
Unlike traditional cloud models where all sensor data is transmitted to remote servers, the edge systems perform the first level of analysis locally, at or near the monitored asset.
This approach drastically reduces latency, limits bandwidth consumption, and guarantees service continuity even when communication networks are unstable.
In critical infrastructure monitoring, these benefits translate into tangible advantages: faster detection of anomalies, higher availability of data and greater operational independence.

Why the Edge matters

In complex infrastructures, decisions must often be made within milliseconds.
When a bridge is under heavy traffic, a turbine experiences thermal expansion, or a tower is subjected to strong winds, the time taken to send raw data to the cloud and receive feedback can be too long to ensure safety.
By embedding computational power on-site, Sensoworks Edge eliminates this dependency.
The system analyses signals in real time and generates local alerts whenever structural or environmental thresholds are exceeded.
This allows engineers to intervene early, or the system itself to act automatically if connected to actuators or control systems.
Moreover, local processing enables contextual understanding: data is analysed alongside environmental parameters such as wind speed, humidity or temperature, allowing the platform to distinguish between harmless events and real degradation.

The Edge/Fog architecture

Sensoworks Edge is built upon a three-tier architecture that ensures reliability and scalability:

- Edge layer, where data is acquired and processed close to the sensors.
- Fog layer, which aggregates and validates data across multiple nodes within a regional domain.
- Cloud layer, responsible for long-term storage, advanced analytics, and system-wide coordination.

This structure distributes intelligence across the network.
Each layer performs specific functions but can operate autonomously when necessary, guaranteeing uninterrupted monitoring even in case of disconnection from the central platform.

Key principles of distributed intelligence

- **Autonomy:** Every node can operate independently, processing and storing data locally.
- **Resilience:** Loss of connectivity does not interrupt monitoring. Data is queued and synchronised automatically once the network is restored.
- **Scalability:** New nodes or sensors can be added without reconfiguring the entire system.
- **Interoperability:** Open protocols (Modbus, OPC-UA, MQTT, REST) ensure seamless integration with existing systems.
- **Security:** End-to-end encryption and role-based access control protect data at every level.

Together, these principles create a monitoring environment where intelligence is not centralised but distributed close to the action, where it is most needed.

From reactive monitoring to proactive intelligence

With traditional systems, data is often analysed after the event.
By contrast, Sensoworks Edge enables real-time interpretation, generating insights as conditions evolve.
When a sensor detects an anomaly, the node immediately correlates the event with other parameters, assesses its severity, and triggers predefined responses.
This evolution transforms monitoring from a passive control process into an active, predictive system capable of understanding its own behaviour and supporting operational decisions with scientific precision.

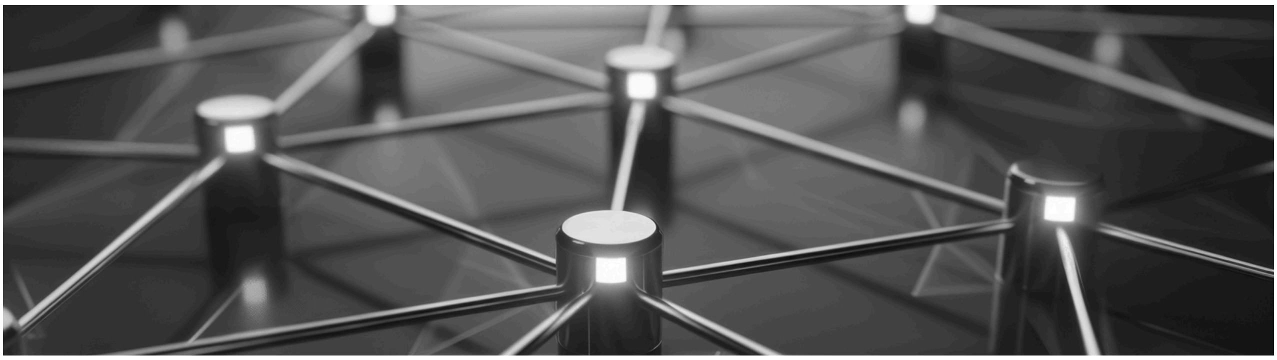
Functional architecture of Sensoworks Edge

The Sensoworks Edge platform is the result of a layered architectural design that unites data acquisition, local intelligence and secure communication in a single operational framework.
It is engineered to guarantee performance, resilience and interoperability across a wide range of infrastructures and environmental conditions.

Hardware Layer

Industrial-grade design

Each Edge node is an industrial device specifically designed for critical field applications.
It operates in extended temperature ranges, with shock and vibration resistance **compliant** with **IEC 60068** and electromagnetic compatibility under **IEC 61000-6-2/4**.
All components are solid-state, fanless and energy-efficient, ensuring durability and low maintenance even in remote or unmanned environments.
Power redundancy is supported through dual inputs and UPS integration, allowing continuous operation during power fluctuations or short outages.
The devices use solid-state drives for persistent local storage, optimised for high-frequency writes typical of monitoring applications.



Sensors and interfaces

The platform supports a broad range of structural and environmental sensors, including:

- Accelerometers (uniaxial and triaxial) for vibration and dynamic response;
- Strain gauges and extensometers for structural deformation;
- Inclinometers and tilt sensors for geometric stability;
- Temperature and humidity sensors for environmental monitoring;
- Pressure transducers and flow meters for hydraulic systems;
- GNSS antennas for precise time synchronisation and positional accuracy.

These sensors can be connected directly or through external data loggers, PLCs or SCADA systems.
Each node supports multi-protocol communication via RS-485, Ethernet, and wireless interfaces such as LoRaWAN, ZigBee, 4G/5G modems, and Satellite links for remote or connectivity-constrained environments.

Data Acquisition and Sampling

Acquisition logic

Data acquisition (DAQ) is handled by the Sensoworks Edge Data Layer, a modular component that reads sensor inputs, converts analogue signals, and stores them locally.
Sampling frequencies are configurable per channel, reaching up to 1 kHz for high-resolution dynamic monitoring.
Signals are timestamped in ISO 8601 UTC format, ensuring temporal coherence between distributed assets.
Time synchronisation is achieved through NTP or GNSS services, maintaining drift below 1 millisecond across multiple nodes.

Pre-conditioning and validation

Before data enters the analytical pipeline, it undergoes a pre-conditioning phase.
Automatic calibration routines check baseline values, detect zero-drift and normalise unit scales.

Noise and spikes are removed using adaptive digital filters such as low-pass, band-pass or median filters based on the type of sensor and the frequency of interest.
Cross-channel correlation ensures internal consistency among related signals (e.g., vibration vs. acceleration vs. temperature).
This process guarantees that only valid and meaningful information proceeds to analysis, improving diagnostic reliability and reducing false events.

Buffering and continuity

Each node features a circular ring buffer that stores up to 30 days of raw and processed data, ensuring continuity in case of network interruption.
When communication is re-established, data is automatically synchronised with the central platform, without loss or duplication.
This autonomous buffering capability allows continuous operation even in isolated sites, supporting Sensoworks' principle of "monitoring without dependency."

Pre-processing and Data Conditioning

Once acquired, the data enters the pre-processing layer.
Here, real-time routines transform raw signals into structured, high-quality datasets suitable for diagnostic interpretation.
The pre-processing chain includes:

- **Filtering:** Adaptive filters eliminate noise while preserving signal integrity.
- **Normalisation:** Sensor readings are converted to standard engineering units (for example m/s^2, °C, mm, Pa).
- **Correlation:** Multi-sensor relationships are identified (for example, the link between temperature variation and material strain).
- **Event tagging:** Each dataset is labelled with metadata, timestamp, node ID, and location, preparing it for analytics.

This continuous conditioning produces a coherent and synchronised data stream that reflects the real behaviour of the monitored structure in its operational context.

Analytical and Diagnostic Models

Time-domain analysis

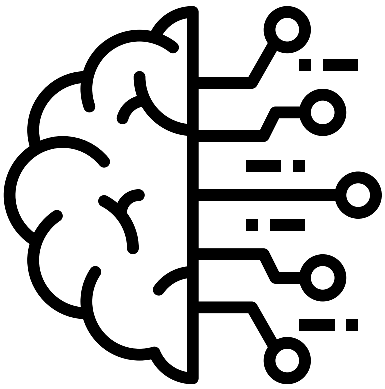
In the time domain, Sensoworks Edge calculates standard statistical metrics such as RMS, peak acceleration, displacement and temperature variance.
These metrics are the first indicators of anomalous conditions or dynamic changes.

Frequency-domain and modal analysis

The platform performs Fast Fourier Transform (FFT) to analyse the spectral content of signals and identify dominant frequencies.
More advanced algorithms such as Operational Modal Analysis (OMA) are applied to determine natural frequencies, damping ratios and mode shapes of structures under operational loads.
OMA analysis enables detection of stiffness loss, connection deterioration and material fatigue even when no external excitation is applied.
It uses natural vibrations (traffic, wind, ground motion) as input, transforming them into diagnostic insight.

Machine learning and predictive models

Beyond deterministic methods, Sensoworks Edge integrates lightweight machine learning models for predictive analysis.
These algorithms identify trends in frequency shifts, amplitude decay or temperature drift, estimating the probability of degradation over time.
The system continuously updates these models as new data arrives, improving accuracy without manual recalibration.
Each iteration refines the baseline, allowing the system to differentiate between normal environmental variability and genuine anomalies.



Event Management and Threshold Handling

Threshold definition and classification

Every measured parameter is associated with predefined thresholds, which can be static (fixed engineering limits) or dynamic (adaptive, based on statistical variance).

When a reading surpasses a limit, the event manager classifies it according to severity as a warning, alert, or critical notification.

For example:

- A warning indicates deviation from normal behaviour.
- An alert suggests a sustained or accelerating change.
- A critical event triggers immediate notification and potential intervention.

Correlation and contextual analysis

Each event is validated by cross-referencing data from multiple sensors.

A vibration peak, for instance, is only confirmed as an alarm if it correlates with temperature or load conditions.

This reduces false positives and ensures that alerts represent true operational risks.

Procedures and escalation

When a threshold is exceeded, the system activates predefined procedures:

- Local alarm generation with flashing or acoustic indicators (if available).
- Automatic data logging of the full time window (pre- and post-event).
- Notification dispatch via MQTT, REST API, email or SMS.
- Event escalation to maintenance platforms or SCADA for intervention.

All alerts are timestamped, archived, and made accessible for post-analysis through the central dashboard.

Communication and Data Flow

Protocols and transmission

Data transmission is handled through open and secure communication standards:

- **MQTT** for asynchronous message publication;
- **OPC-UA** for interoperability with industrial systems;
- **REST over HTTP(S)** for web-based integrations;
- **Modbus TCP/RTU** for legacy devices;
- **LoRaWAN/ZigBee** for low-power wireless networks.

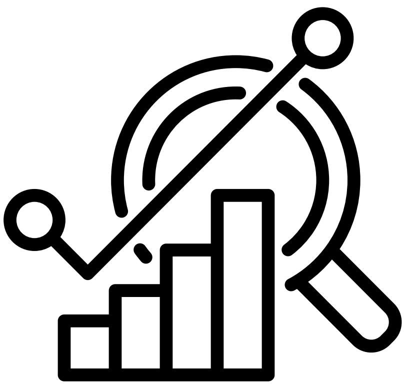
All messages are encrypted with **TLS 1.2+** and compressed to minimise bandwidth usage.
In case of network disruption, queued packets are stored locally and transmitted automatically upon reconnection.

Edge-Fog-Cloud data chain

The data chain operates as follows:

- **Edge layer:** real-time acquisition, filtering and pre-analysis.
- **Fog layer:** aggregation of multiple nodes, cross-validation, and buffering.
- **Cloud layer:** historical storage, advanced analytics, and global supervision.

Each layer communicates bidirectionally, allowing both upstream (data flow) and downstream (configuration updates, model distribution) operations.
This ensures consistency between local and central intelligence, maintaining a unified monitoring environment across distributed assets.



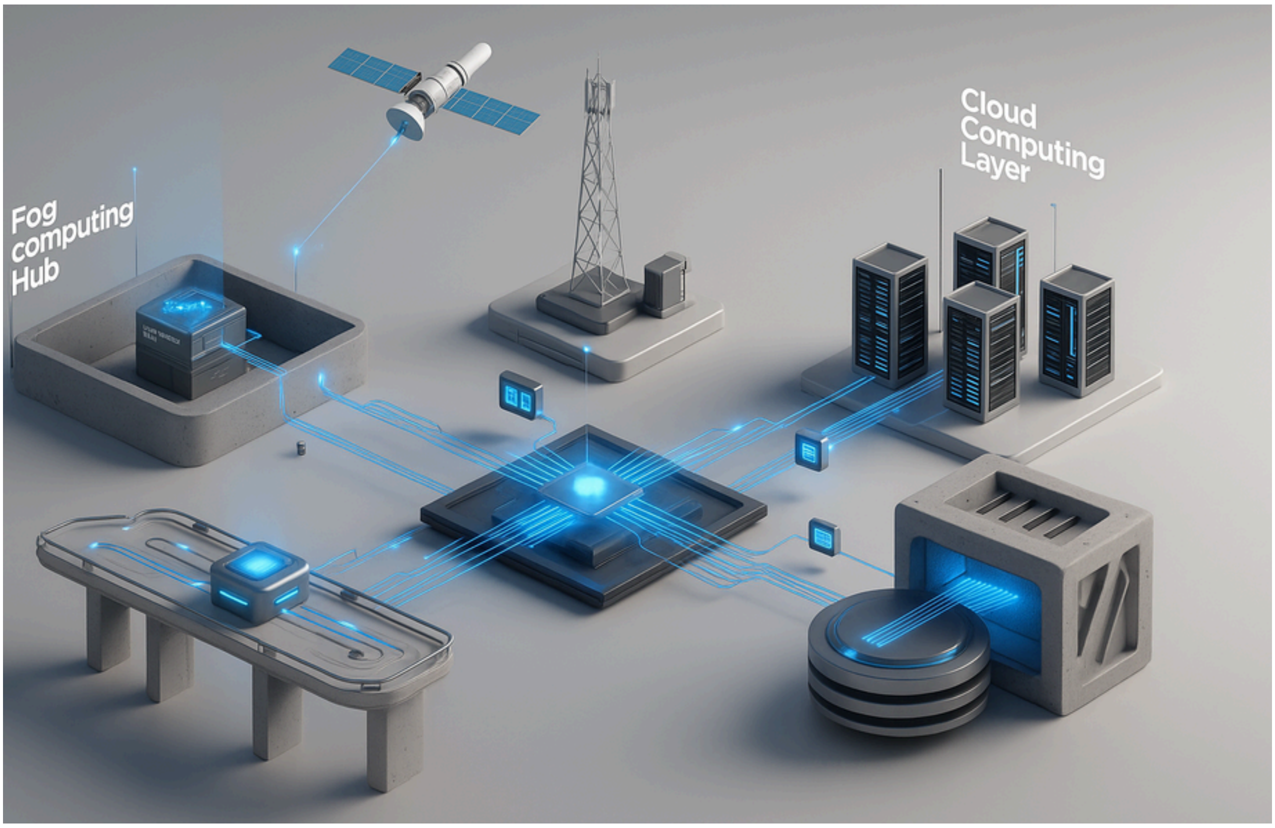
Summary of Functional Capabilities

Sensoworks Edge combines advanced field analytics with robust communication and control capabilities.

Its architecture enables:

- Continuous multi-sensor acquisition up to 1 kHz.
- Real-time modal and frequency analysis directly at the asset.
- Adaptive threshold management and predictive modelling.
- Secure, encrypted data transmission via standard protocols.
- Local buffering for 30 days of autonomy.
- Full interoperability with SCADA, asset management and cloud analytics platforms.

In essence, Sensoworks Edge transforms raw physical signals into operational intelligence, ensuring that every monitored structure from bridges to turbines can think, respond and evolve.



System Operations

Efficient operation of a distributed infrastructure monitoring system depends on its ability to guarantee continuity, integrity and security not only in ideal conditions, but especially when things go wrong.
The **Sensoworks Edge** operational framework has been designed around these principles, ensuring that every element of the system from local sensors to cloud analytics behaves predictably, securely and transparently.

Security and Access Management

Security by design

Every Sensoworks Edge node is developed following the “security-by-design” principle.
Cyber-protection is not an add-on; it is embedded into every layer of the architecture, from the firmware to the communication stack and the data model.
Each component undergoes hardening to minimise its attack surface and enforce robust identity management.

Authentication and authorisation

Access to each node, Fog gateway or Cloud interface is managed through **Role-Based Access Control (RBAC)**.
Users are assigned permissions according to their function, operator, analyst, administrator with clearly defined privileges.
Authentication uses **OAuth 2.0** or **certificate-based credentials,** ensuring both security and traceability.
All access attempts are logged, timestamped and archived for auditing.
Two-factor authentication can be activated for sensitive operations, such as remote firmware updates or parameter modifications.

Data encryption and integrity

Data confidentiality and integrity are maintained at all times through end-to-end encryption.
At rest, local databases are encrypted using **LUKS (Linux Unified Key Setup)** or **dm-crypt**, protecting stored data even in the event of physical theft.

During transmission, all packets are secured with **TLS 1.2+**, preventing interception and tampering.
Digital signatures are applied to software packages and configuration updates to ensure authenticity and prevent unauthorised modifications.

Backup and Recovery

Local autonomy

Sensoworks Edge nodes are built for autonomy.
Each device maintains a **local backup** of raw and processed data within a circular buffer capable of storing up to 30 days of measurements.
This ensures that no information is lost even during extended network outages.

Recovery mechanism

When connectivity is restored, the node automatically synchronises with the Fog or Cloud level.
The system performs a **differential comparison** between local and central data stores, identifying missing records and updating them without duplication.
This method guarantees continuity of datasets and preserves historical integrity.

Redundancy and fail-safe design

Redundancy extends beyond data.
Power inputs, communication channels and even computational processes are duplicated wherever possible.
Edge devices can operate in fail-over mode, while Fog servers replicate critical data across redundant storage volumes.
This approach provides resilience against both hardware failures and human error.

Integration with External Platforms

Open interfaces

Integration is fundamental to Sensoworks' philosophy.
The platform communicates through standard and open protocols, ensuring interoperability with existing systems and future expansions.
APIs are exposed via **RESTful endpoints**, allowing external platforms to retrieve or push data securely.

SCADA and industrial connectivity

Sensoworks Edge can act as both a data source and a supervisory client in SCADA ecosystems.
Using **OPC-UA** and **Modbus TCP/RTU**, it exchanges data with industrial controllers, energy management systems and automation units.
This enables hybrid environments where Edge intelligence complements traditional supervisory control.

Smart city and IoT platforms

Through **MQTT brokers** and **HTTP webhooks**, the platform integrates with smart city frameworks, CMMS (Computerised Maintenance Management Systems), GIS tools and third-party analytics dashboards.
All integrations are version-controlled and fully documented via **OpenAPI specifications**, ensuring transparency and replicability.

System Logging and Supervision

Comprehensive logging

Every activity on the platform, from sensor readings to system events, is recorded through a hierarchical logging system.
Log records are grouped into three primary categories:

- **Operational logs:** covering acquisition rates, uptime, node temperature and disk usage.
- **Security logs:** documenting access attempts, authentication failures and permission changes.
- **Analytical logs:** including processing anomalies, threshold activations and model updates.

Each log entry is enriched with a timestamp, node identifier and severity classification. Logs can be exported in **CSV** or **JSON** formats or streamed directly to **Syslog** servers for centralised oversight and long-term retention.
To ensure full auditability, each log file undergoes a cryptographic hashing process and is paired with a secure, trusted timestamp. This combination allows any subsequent alteration, whether partial or complete, to be detected immediately.

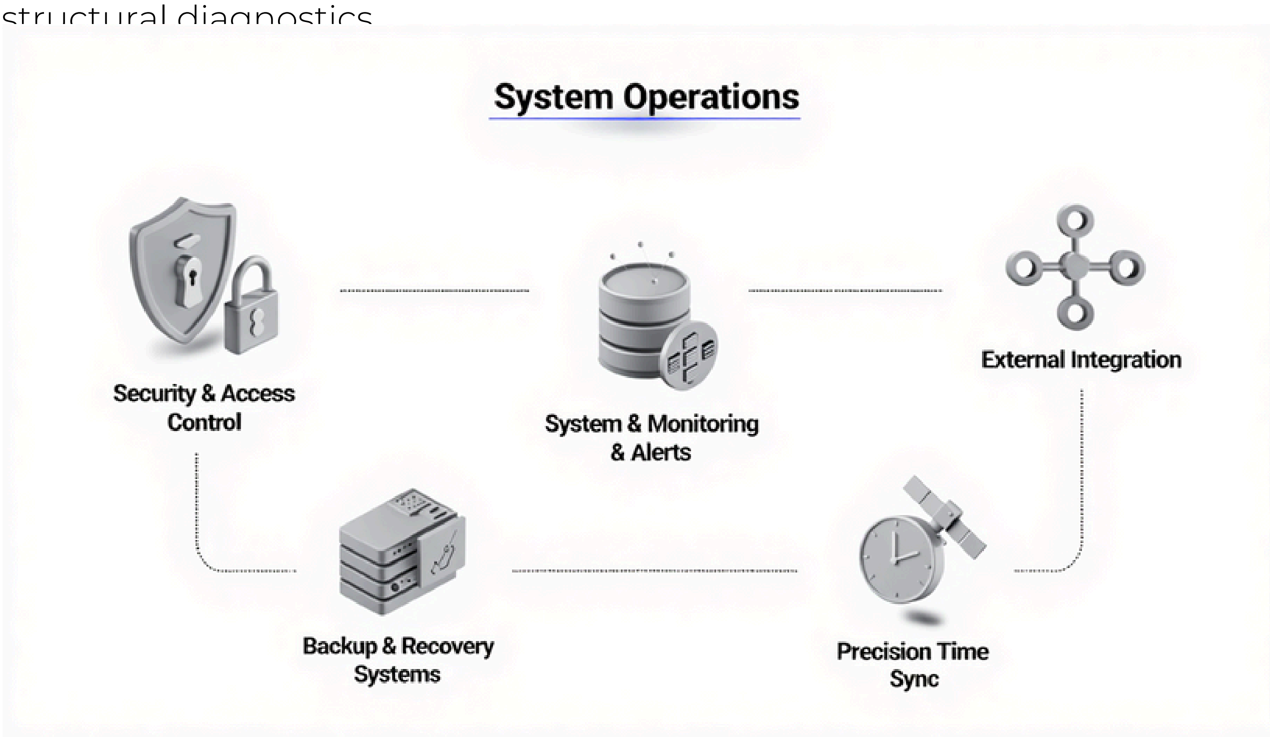
The result is tamper-evident logging that preserves integrity, supports reliable forensic inspection and guarantees long-term verifiability of all operational records.

Health monitoring

A **watchdog service** continuously monitors CPU load, memory availability and communication uptime.
If thresholds are exceeded, the system triggers an internal alert, restarts specific processes or sends a notification to the operations team.
This self-supervising design minimises downtime and prevents cascading failures.

Time Synchronisation

Precise time alignment is essential for multi-sensor correlation and event analysis.
All Sensoworks nodes maintain a synchronisation hierarchy using **NTP** as the primary protocol and **GNSS** as backup.
Drift is typically under 1 ms across distributed devices.
When connection to external time servers is unavailable, nodes rely on internal oscillators calibrated against the last known reference.
Once synchronisation is restored, datasets are automatically corrected for any offset, ensuring absolute temporal coherence.
Time integrity ensures that modal analyses spectral comparisons and cross-site correlations remain scientifically valid, a critical requirement for structural diagnostics.



Data visualisation and user interaction

The value of a monitoring system lies not only in the data it collects, but also in how that data can be interpreted and used.
Sensoworks Edge offers a unified, intuitive and technically rigorous interface for engineers, analysts and decision makers.

Dashboard and Reporting

Interactive dashboards

The Sensoworks dashboard aggregates multi-layer data into visual elements that represent the real-time condition of infrastructures.
Through configurable widgets, users can visualise vibration spectra, temperature profiles, pressure trends and threshold statuses.
The interface supports hierarchical navigation from national networks down to individual sensors enabling both macro and micro-analysis.
Dashboards are fully responsive, accessible from desktop, tablet and mobile, and support role-based visibility, ensuring that each user accesses only relevant and authorised information.

Reporting engine

Automated reporting modules generate summaries on a **daily, weekly or monthly basis**, depending on configuration.
Reports include:

- System uptime and connectivity metrics;
- Event frequency and severity;
- Evolution of modal parameters (frequency, damping, amplitude);
- Maintenance recommendations and upcoming interventions.

Reports can be **exported in PDF** or **Excel format** and can be automatically sent via email to authorised recipients.

Alarm Management

Centralised view

All alerts and events generated at the Edge level converge into a central Alarm Manager.
This tool classifies, filters and tracks notifications based on severity, category and origin.
Operators can acknowledge, comment and close alarms directly through the interface, ensuring full traceability.

Event lifecycle

Each alarm maintains a lifecycle:

- **Detection:** Triggered locally by the Edge node.
- **Validation:** Confirmed through correlation across multiple sensors.
- **Notification:** Communicated via dashboard, email or API.
- **Resolution:** Marked as addressed with details of intervention.

This workflow guarantees that no critical event remains unattended and that post-event analysis can trace every step from detection to closure.

Cloud and Analytics Platform

Long-term storage and analysis

At the cloud level, all processed data is stored in a high-availability database cluster.
This environment supports long-term trend analysis, infrastructure benchmarking, and data correlation across assets.
Machine learning models trained in the cloud are periodically deployed to edge nodes for continuous improvement, enabling a feedback loop that keeps field information up to date.

Cross-asset visibility

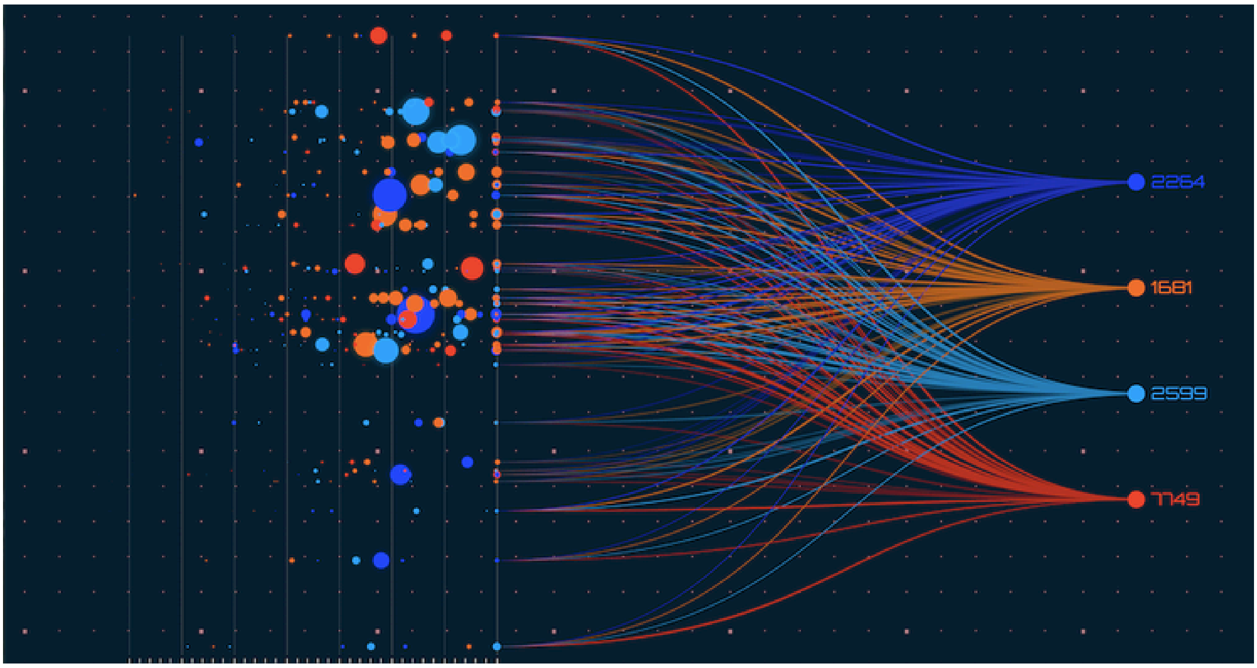
Operators can compare the performance of multiple structures, such as similar bridges in different regions, to identify recurring patterns or structural anomalies.
This cross-sectional visibility transforms maintenance strategies from isolated interventions to systemic optimisations.

User Experience and Human-Machine Interaction

The design of Sensoworks Edge's visual interface reflects the company's core principle: **Humanizing Things.**
Complex data must be comprehensible, actionable and directly relevant to human decision-making.
Every element, from chart design to alarm colours, is carefully crafted to balance precision and clarity.
Engineers can dive into detailed spectral analyses, while managers can view high-level KPIs on the same platform.
By reducing the cognitive load and presenting insights rather than raw numbers, the interface enables faster, more confident decisions, aligning technology with human intuition.

Data Sharing and Collaboration

Sensoworks Edge facilitates collaboration between teams and organisations.
Through secure sharing mechanisms, data can be exported to research institutions, public agencies or partner companies for joint analysis.
Access rights are granular and revocable, ensuring compliance with privacy and confidentiality policies.
This collaborative capability extends the impact of the monitoring system, supporting innovation across the entire infrastructure ecosystem.



Architecture and method

A multi-layer design for continuous intelligence

The **Sensoworks Edge** platform follows a **multi-layer architecture** designed to ensure resilience, scalability and analytical depth.
Its structure is composed of **Edge**, **Fog** and **Cloud** tiers and provides both autonomy and coordination across distributed infrastructures.

At the **Edge layer**, data is acquired, filtered and processed directly on-site. Each node operates autonomously, executing real-time analytics even in the absence of network connectivity.

The **Fog layer** consolidates data from several Edge nodes, performing regional cross-validation, local storage replication and distributed configuration management.

The **Cloud layer** oversees global analytics, historical data management, model training, and system orchestration.
This approach balances decentralisation and control: intelligence resides where it is most needed, while long-term governance remains centralised and secure.

Data Integrity and Cybersecurity

End-to-end protection

Data security begins at the sensor level.
All communications, from acquisition to transmission, are encrypted using **TLS 1.2+**, while data at rest is protected by **AES-256 encryption** within local and cloud databases.
Integrity is maintained through **SHA-256 checksums** and **cryptographic signatures**.
Every transaction, configuration updates, firmware deployments, and event notifications are verified to prevent tampering or injection attacks.

Identity and access control

Authentication is enforced through multi-layer credentials (certificates, OAuth tokens, or hardware keys).
Permissions follow a strict Role-Based Access Control (RBAC) structure, ensuring that only authorised personnel can access or modify data.
Audit logs document every access attempt, guaranteeing accountability across the system.

Compliance and resilience

Sensoworks Edge aligns with key international standards such as **IEC 62443** for industrial cybersecurity, **ISO 27001** for information security management, and **GDPR** for data protection.
Resilience is achieved not only through encryption but also through redundant duplicated communication channels, mirrored data repositories, and autonomous failover mechanisms at every layer.

Operational Methodology

Measure, Understand, Predict, Act

The Sensoworks methodology transforms raw measurements into operational decisions.
It can be summarised as a continuous loop:

- **Measure:** Acquire structural and environmental data via distributed sensors.
- **Understand:** Correlate data in real time to establish operational context.
- **Predict:** Use models to forecast degradation or performance decline.
- **Act:** Generate alerts, trigger interventions or optimise maintenance scheduling.

This cycle allows operators to shift from reactive to proactive management, ensuring safer and more efficient infrastructures.

An adaptive learning system

Machine learning algorithms continuously refine analytical thresholds.
The system learns the normal behaviour of each asset, adjusting its models as conditions evolve, seasonal variations, ageing materials, and changing traffic patterns.
This self-adaptive behaviour enhances diagnostic precision and reduces false positives, particularly in dynamic environments.

Scalability and Maintenance

Horizontal and vertical scalability

The modular design of Sensoworks Edge allows easy expansion.
Additional sensors or nodes can be deployed without altering the system's overall configuration.
Edge units automatically register with Fog gateways and the central Cloud, synchronising time, configuration and analytical models.

Remote maintenance and updates

All nodes can be remotely maintained through secure over-the-air (OTA) updates.
Firmware and analytical models are digitally signed and distributed with rollback protection.
Diagnostic logs and performance metrics enable predictive maintenance of the monitoring system itself ensuring not only the health of infrastructures but also of the monitoring network.

Interoperability and Integration

Sensoworks Edge was conceived as an open ecosystem.
It integrates seamlessly with third-party systems via **REST APIs, MQTT brokers, OPC-UA servers, or Modbus gateways.**
This flexibility enables data sharing between infrastructure operators, public agencies and private research institutions.
The platform's architecture supports the creation of **Digital Twins**, with dynamic virtual models that mirror the physical behaviour of assets in real time.
By coupling field data with simulation models, operators can visualise future scenarios and test predictive maintenance strategies with high accuracy.

Case studies, the Edge in action

Each deployment of Sensoworks Edge is a proof of its adaptability across diverse environments, from seismic coastal areas to isolated mountain valleys.

23 Apennine viaducts

Context

Across a southern coastal region of the Apennines, twenty-three viaducts connect strategic routes for both freight and civil transport.

The area is known for its complex topography and seismic exposure, where humidity, salt corrosion and continuous heavy traffic accelerate structural fatigue.

Before, inspections were conducted manually and intermittently, producing fragmented information and preventing long-term assessment of the viaducts' health.

The main challenge was to transition from episodic inspections to a **continuous, high-frequency monitoring system** capable of identifying micro-anomalies in real time before they evolved into structural damage.

Engineers also had to deal with limited on-site connectivity, complex geometry, and the need to monitor dozens of bridges simultaneously without increasing operational costs.

Sensoworks **deployed a network of Edge nodes connected to over 1,700 sensors, averaging 75 per bridge, including accelerometers, inclinometers, strain gauges, and temperature probes.**

The system performs **real-time data acquisition at 100 Hz**, capturing every vibration and deformation cycle of the structure.

Through **Operational Modal Analysis (OMA)**, the "dynamic signature" of each bridge is continuously analysed, like its natural frequencies, modal shapes and damping coefficients.
The Edge layer executes local diagnostics, comparing each dataset against historical baselines.
When stiffness loss or frequency shift beyond the tolerance threshold is detected, the system triggers an automatic alert and stores the complete time window of the event.
All processed data are compressed and transmitted to the Fog gateway, which aggregates results and synchronises them with the cloud once connectivity is available.
At the software level, Sensoworks Edge combines **time-domain processing (RMS, peaks, kurtosis) with frequency-domain analytics (FFT, OMA, PSD).**
This hybrid approach enables engineers to isolate transient vibrations from permanent modal changes.
Dynamic reports are automatically generated for each structure, including:

- Frequency drift tracking (±0.3 Hz accuracy);
- Cross-correlation between vibration and temperature variation;
- Damping decay curves over time.

Visual dashboards allow operators to compare the response of all 23 bridges at once, identifying clusters of similar anomalies, a feature essential for network-scale asset management.

Results and Impact

In the first six months of operation:

- **0 emergency closures** were recorded.
- **45% fewer on-site inspections** were required.
- **30% reduction** in **reactive maintenance** interventions.
- Early detection of stiffness loss in **3 of the monitored structures**, enabling corrective action before damage propagated.

The deployment proved that predictive maintenance, when powered by distributed intelligence, not only enhances safety but also extends the service life of critical assets while optimising budget allocation.

What the Data Really Tells Us Today

High-frequency sampling on seventy-five instruments per structure revealed remarkably consistent dynamic behaviour. Modal shapes remain stable under standard loading, while variations in natural frequencies and damping correlate consistently with traffic intensity, thermal gradients, and wind exposure.

The system detects subtle modal variations that, although imperceptible in visual inspections, reflect early changes in stiffness distribution and structural boundary conditions.

The absence of emergency closures is not coincidental and indicates that all measured deviations remained within the elastic spectrum of the structure. Combined with a reduction in extraordinary inspections, the dataset confirms that the viaducts behaved predictably and that weak signals are now detected long before they turn into operational anomalies.

OMA has proven particularly effective in detecting micro-changes in structural behaviour. Frequency variations of a few tenths of a hertz, normally ignored as noise, are now measurable indicators of the evolution of structural conditions.

Why This Matters Tomorrow

As behavioural baselines become statistically robust, operators will gain the ability to distinguish reversible environmental drift from early-stage structural deterioration with much higher confidence.

The transition from time-based to behaviour-based maintenance becomes practical and defensible: interventions are triggered by physics, not by age or routine.

Budget planning becomes more accurate, high-risk zones can be prioritised intelligently, and the probability of undetected deterioration drops significantly.

For the mobility system, this means fewer disruptions, stronger resilience during extreme climatic events, and improved reliability along a critical transport artery.

Ultimately, these viaducts evolve from periodically inspected assets into continuously interpreted systems, structures that disclose their condition through measurable dynamics rather than visible symptoms.

Apennine tunnel

Context

Built through the northern Apennines, a strategic road tunnel supports thousands of vehicles every day.
Subjected to humidity, vibrations and periodic flooding, it represents one of the most demanding environments for sensors and electronic equipment.
Before Sensoworks Edge, maintenance teams relied on weekly inspections and SCADA logs that were often incomplete or delayed.
The main issue was a **lack of visibility**: no continuous monitoring system existed, and any malfunction could remain undetected for hours.
Additionally, the absence of reliable mobile or fibre connectivity made it impossible to use traditional cloud-based systems.
The objective was to create a fully autonomous monitoring setup capable of analysing and correlating environmental and structural parameters in real time, even with zero external communication.
Sensoworks installed a distributed Edge system integrated with **40 structural sensors** and **20 environmental probes** measuring temperature, humidity and air quality.
The Edge nodes process data locally, applying correlation algorithms that link environmental fluctuations (rainfall, pressure changes) with physical stress on the tunnel lining.

Each node performs:

- Continuous acquisition at 100 Hz;
- Real-time event correlation;
- Local threshold validation and alarm triggering;
- Periodic data aggregation for post-analysis.

The Edge software executes **adaptive thresholding** based on seasonal baselines, meaning that an alert is triggered only when a parameter deviates beyond its dynamic normal range.

For example, vibration amplitude may naturally increase by 10% during high humidity, and the system learns this behaviour and adjusts its thresholds automatically.

When connectivity is absent, Edge devices continue to operate independently.

They queue events and synchronise once communication is re-established through a **satellite backhaul**.

Results and Impact

In the first operational semester:

- **Zero unplanned closures** occurred.
- Maintenance **costs** were **reduced by 40%**, mainly due to fewer on-site visits.
- **Response time** to detected anomalies dropped from 12 hours to under 20 minutes.
- The tunnel remained operational through multiple heavy-rain events without incident.

By processing and interpreting data directly on site, the system turned one of the region's least accessible infrastructures into a **fully self-aware asset.**

What the Data Really Tells Us Today

Continuous structural and environmental monitoring has clarified the relationship between rainfall, infiltration onset and deformation patterns, converting what was once anecdotal correlation into quantifiable evidence.

What the Data Really Tells Us Today

The system captures early-phase water ingress behaviour hours before visible signs appear, demonstrating that the tunnel lining responds to hydrostatic changes in a measurable and repeatable manner.

The 40% reduction in reactive interventions confirms that many "unexpected" events were in fact preceded by detectable structural and environmental precursors.

Most importantly, the lack of terrestrial connectivity has historically been a critical blind spot that no longer compromises visibility, thanks to the Edge processing that ensures the observability in real time of infiltration dynamics, thermal shifts, and crack propagation trends.

Why This Matters Tomorrow

Over time, the tunnel will develop a predictive behavioural model, allowing operators to forecast infiltration peaks based on weather patterns, material response, and environmental cycles.

Interventions can be planned before deterioration accelerates, reducing the risk of sudden closures or closures during storms and improving the long-term durability of the lining with tunnel monitoring that ensures continuity.

For users, this translates into safer travel and fewer disruptions in adverse conditions, improving the usability of the infrastructure.

On a larger scale, the case redefines the meaning of "remote tunnel monitoring," demonstrating that even underground structures that are difficult to access can achieve high levels of operational transparency and resilience, becoming "smart infrastructure."

Telco tower

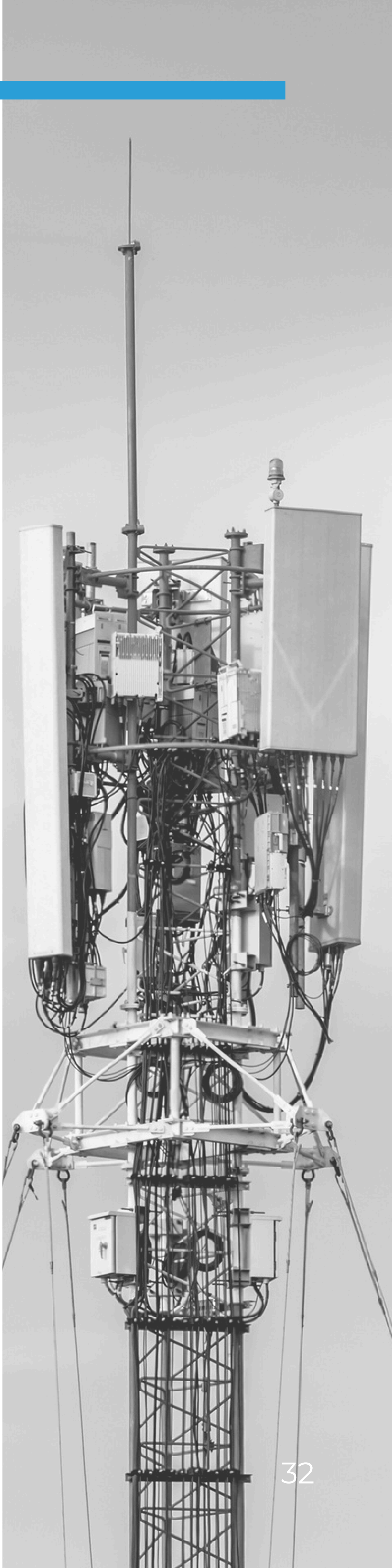
Context

Telecommunication towers are exposed to some of the harshest environmental conditions: wind gusts, temperature fluctuations, lightning and, in some areas, seismic motion.
Maintaining their structural integrity and service continuity is critical, particularly for emergency communication networks.
A 90-metre tower in a remote coastal zone presented recurring oscillations during high winds.

Previously, inspection campaigns could not quantify whether these were safe elastic responses or early signs of structural fatigue.
The goal was to establish a **quantitative, real-time monitoring system** capable of correlating vibrations with meteorological data and detecting stiffness loss before it became visible.

Due to poor mobile coverage, the system had to be capable of operating autonomously and transmitting via satellite.
Sensoworks Edge **equipped** the **structure with 60 dynamic sensors** distributed along its height:

- Accelerometers and inclinometers for dynamic displacement;
- Temperature and wind sensors for environmental correlation.



Sampling was configured at **100 Hz**, generating high-resolution vibration datasets.
Each Edge node runs **Operational Modal Analysis (OMA)** continuously, comparing current modal frequencies with reference patterns.
When deviations exceed a certain percentage, an internal alert is triggered, validated across multiple nodes to avoid false positives.
The platform combines OMA with **Power Spectral Density (PSD)** and **short-time Fourier analysis** to capture evolving frequency behaviour during wind gusts.
All events are timestamped and logged, while **satellite transmission** ensures that even without terrestrial connectivity, critical data reaches the cloud.
Edge analytics quantify:

- Frequency shifts over time (accuracy ±0.05 Hz);
- Correlation between wind velocity and tilt angles;
- Structural damping ratio and fatigue trend estimation.

Results and Impact

Since deployment:

- **30% fewer emergency dispatches** were required.
- **Predictive maintenance** scheduling **improved** tower availability **by 20%**.
- System **uptime reached 99.8%**, even with intermittent network coverage.
- Over **1 TB of vibration data** has been analysed locally, reducing cloud traffic by 85%.

What the Data Really Tells Us Today

The tower shows a marked sensitivity to wind excitation, with stable modal shapes under nominal conditions and predictable displacements during high-intensity gusts.
High-frequency data reveal the influence of both wind turbulence and thermal variation on the tower's modal frequencies, phenomena that are traditionally underestimated during scheduled inspections.
The system accurately distinguishes between benign modal drift and early indicators of structural deterioration, such as loosening of connections, loss of rigidity, or micro-movements of the foundations.

Crucially, the tower maintains full interpretability without terrestrial connectivity, thanks to the satellite connection, demonstrating the robustness of the architecture in exposed, isolated, or wind-critical locations.

Why This Matters Tomorrow

As behavioral fingerprints become more refined, operators will obtain a highly reliable baseline against which any deviations can be identified promptly with a minimum number of false positives.
This will enable targeted inspections, more accurate maintenance window planning, and a reduction in emergency interventions.
For end users, the effect will be a more stable communication service, especially during storms or network load peaks.
At the network level, this information will optimize tower maintenance strategies, allowing operators to prioritize information that highlights significant dynamic changes rather than relying solely on age or topology.

Hydroelectric plant

Context

In a mountainous Region of Northern Italy, a hydroelectric facility operates with two turbines and a lifting system feeding a high-altitude reservoir.

The plant's location, isolated, surrounded by steep terrain, offered no mobile or fibre connectivity, forcing operators to conduct weekly manual inspections to verify system performance.

The result was high operational costs, inconsistent data and limited situational awareness.

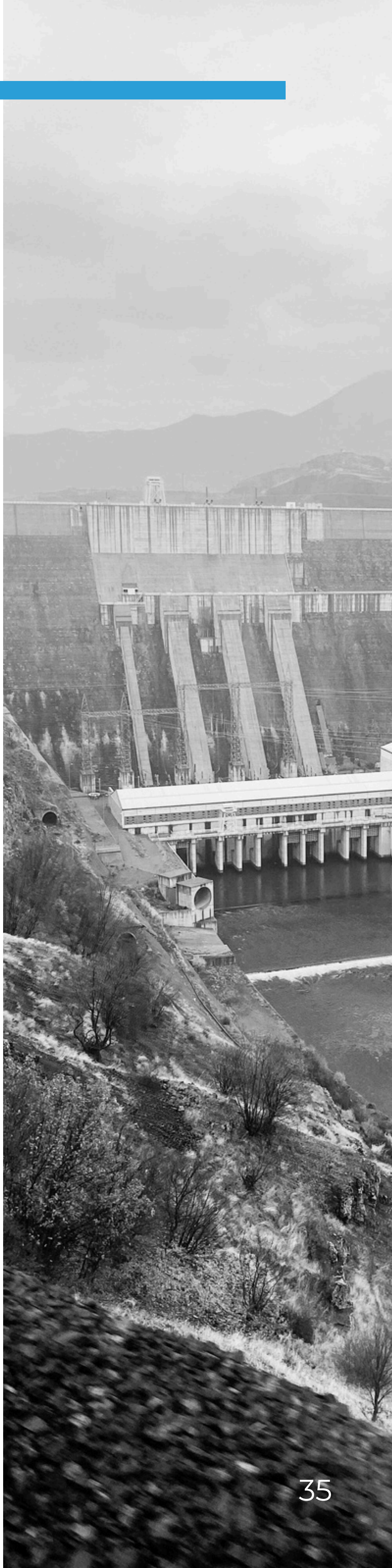
The objective was to achieve **full remote visibility and control** without modifying the existing infrastructure.

The system needed to integrate with the plant's local **SCADA** and function autonomously, even for weeks without external communication.

Sensoworks Edge was installed to interface directly with the SCADA and monitor:

- Turbine vibration and temperature;
- Pressure and status of the hydraulic lifting actuators;
- Power generation and efficiency indicators.

Edge nodes analyse this data locally, applying **trend-based diagnostics** that evaluate performance decay and detect parameter drifts.



A **bidirectional satellite gateway** connects the plant to the cloud, allowing two-way communication for updates, commands and data synchronisation.
The platform executes hybrid analytics combining deterministic rules (thresholds, efficiency ratios) with machine learning models trained on historical data.
When deviations in turbine vibration or hydraulic pressure exceed normal variance, alerts are generated and maintenance tickets are issued automatically.
Data visualisation dashboards display energy output, machine efficiency, and predicted maintenance windows.

Results and Impact

In the first year of operation:

- **75% reduction** in site **visits** by technicians;
- **Continuous remote control** of all critical components;
- **12-month ROI**, due to reduced downtime and travel costs;
- Creation of a historical dataset covering over 8,000 operating hours, now used for predictive modelling.

The system has effectively turned a remote hydroelectric plant into a **digitally self-managing facility**, proving that even the most isolated infrastructures can achieve full operational awareness when powered by distributed intelligence.

What the Data Really Tells Us Today

Continuous monitoring has revealed performance patterns that weekly inspections were unable to detect, making it possible to analyse correlations between vibration signals, hydraulic pressure variations, actuator behaviour, and thermal drift.
This data reveals the early progression of mechanical degradation (imbalance, bearing wear, cavitation tendency) well before it has an impact on energy production.
The integration with the local SCADA system provides a complete, real-time operational picture, consolidating physical and operational indicators.

The 75% reduction in on-site visits confirms that the plant remains stable and interpretable even without access to the terrestrial network, a fundamental requirement for mountain hydroelectric plants.

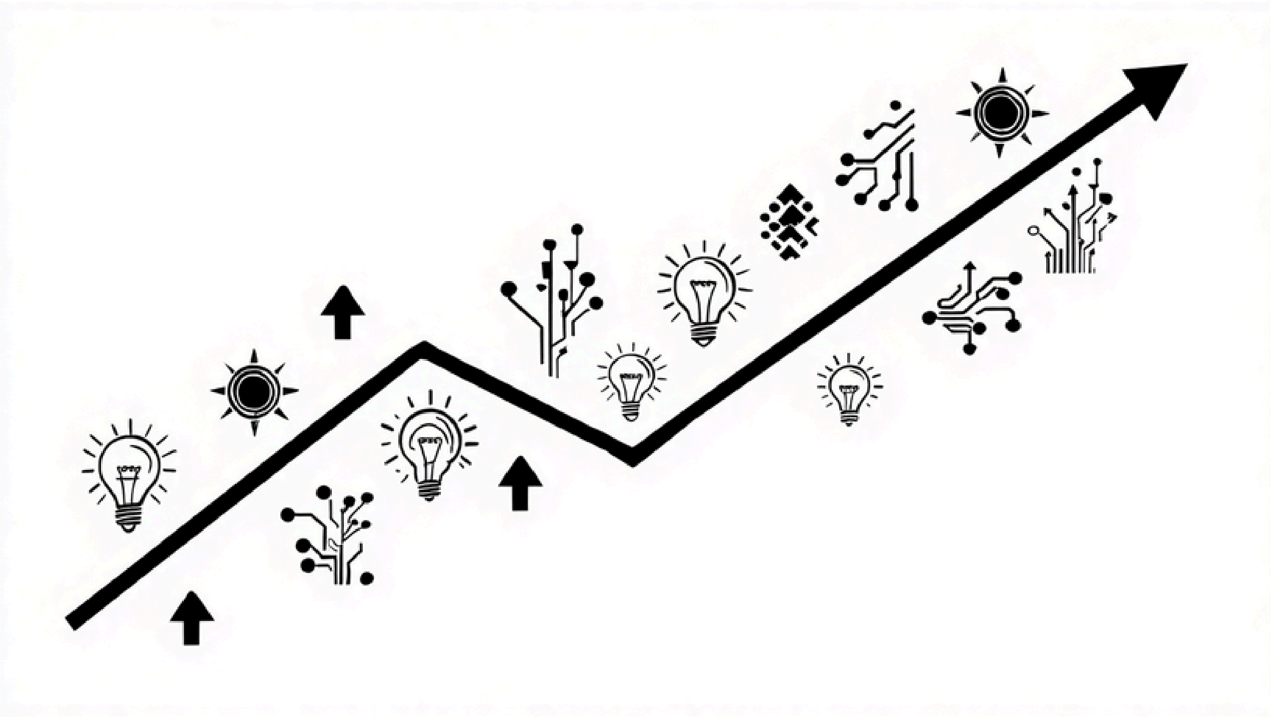
Why This Matters Tomorrow

Thanks to continuous monitoring, the plant will be able to identify degradation paths promptly and accurately, allowing intervention before efficiency losses or the likelihood of failures increase.

Component life is extended, operational continuity becomes more predictable, and maintenance can be planned with significantly less uncertainty.

For the energy system, this means a more reliable and resilient supply, particularly in regions where hydropower is the primary source.

For local communities, this translates into fewer service interruptions and greater stability during peak demand or adverse conditions.



Conclusions and Outlook

Sensoworks Edge implementations in 2025 demonstrate that distributed intelligence is not an experimental technology, but a new operating paradigm.
Whether it's bridges, tunnels, towers or power plants, the principle is the same: when intelligence moves closer to the field, infrastructure gains awareness, autonomy and reliability.
Measured over hundreds of operational days, results consistently show:

- **Latency reduction** up to 90% compared to cloud-only systems.
- **Maintenance cost savings** exceeding 40%.
- **Service continuity** in environments with zero terrestrial connectivity.

But beyond the numbers, Sensoworks Edge has proven a concept: that **technology can adapt to the environment, not the other way around.**
Looking ahead to 2026, Sensoworks will continue to strengthen its network of partnerships and projects, extending the reach of real-time intelligence across new infrastructures and new territories.
The goal remains unchanged: to ensure that technology keeps pace with the world it serves, enabling safety, continuity and trust for the communities that depend on it.

Humanizing Things.

sensoworks